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Review

Essential oils from *Eucalyptus* species: a review of their activities, applications, and the Brazilian market

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ABSTRACT

Essential oils are volatile, lipophilic substances mainly composed of terpenes, derived from secondary metabolism. Widely used in pharmaceutical, agricultural, and cosmetic industries, essential oils from eucalyptus species are particularly notable for their economic and biological significance. This review explores the antimicrobial, anti-inflammatory, antioxidant, antiviral, and insecticidal activities of essential oils from various eucalyptus species and their isolated constituents, such as eucalyptol and α-terpineol. Because eucalyptus represents 96.7% of the reforested area in Brazil, economic analyses focused on the Brazilian market, highlighting a 25-year trajectory of production and trade, the dominance of eucalyptol-rich oils, and the growing demand for sustainable and high-quality products. Future market prospects include expanding the use of underutilized species, improving oil formulations for enhanced stability and bioavailability, and meeting stringent international quality standards. Addressing these challenges and opportunities underscores the essential role of ongoing research in leveraging eucalyptus essential oils as versatile and sustainable bioresources.

Keywords: composition, essential oils, Myrtaceae, sustainability, terpenes

Introduction

The *Eucalyptus* genus is the most widely cultivated forest genus worldwide (Mateus *et al.*, 2021), and the area of plantation has exceeded 22.57 million ha (Hua *et al.*, 2022). According to the Brazilian Institute of Geography and Statistics (IBGE, 2024), the planted forests in Brazil reached 9.7 million hectares in 2023, with eucalyptus and pine together accounting for covering 96.3% of this area. Eucalyptus alone covers 7.6 million hectares, representing 78.4% of the total area. Eucalyptus is used mainly for the pulp and paper industry and Brazil is the world's largest exporter of pulp, with the top destinations being China, the United States, the Netherlands, and Italy.

Eucalyptus forests serve various purposes, from wood use per se to the extraction of essential oils for use in the pharmaceutical and chemical industries, but the primary use of eucalyptus is as raw material for paper and pulp production. More recently, there has been increased interest in eucalyptus as an

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energy crop due to its rapid growth and biomass accumulation (Pérez-Cruzado *et al.*, 2011). Tab. 1 shows the uses of several eucalyptus species.

The superior silvicultural characteristics of eucalyptus compared to other species are what distinguish the genus. These include rapid growth rate, upright stem, ability to adapt to a wide range of climates and soils, and good wood quality for pulp production (Grattapaglia & Kirst, 2008; Moura *et al.*, 2010).

The term Eucalypt includes species from the genera *Eucalyptus* L'Hérit., *Corymbia* Hill and Johnson, and *Angophora* Cav., with the latter two no longer being subgenera of the first, but rather referred to as genera based on molecular studies (Grattapaglia & Kirst, 2008). The centre of origin for the *Eucalyptus* genus is Australia and nearby islands such as Papua New Guinea, Timor, Indonesia, Tasmania, and the Philippines, providing different species of these genera with adaptation to various soil and climatic conditions, with each species having specific characteristics (Ladiges & Wasshausen, 1996). The term "Eucalyptus" refers to a group of more than 700 species and varieties that belong to the genera *Eucalyptus* and *Corymbia* (Barbosa *et al.*, 2021).

Table 1. Primary uses of the studied *Eucalyptus* species

Species	Purpose
Eucalyptus camaldulensis	Flowers for honey production Sawmill, sleepers, charcoal, posts, stakes, and firewood
Eucalyptus dunnii	Firewood, civil construction (shores), sawmilling/lamination, posts/stakes/posts, cellulose and paper
Eucalyptus exserta	Heavy, hard, and durable wood, useful in constructions
Eucalyptus globulus	Essential oil
Eucalyptus grandis	Firewood, civil construction (shores), sawmilling/lamination, posts/stakes/posts, cellulose and paper
Corymbia henryi	Flowers for honey production, wood for constructions and tool handles
Eucalyptus pellita	Flowers for honey production Wood for constructions and structures
Eucalyptus resinifera	Sawmill, mobile constructions, crates, sleepers, posts, and stakes
Eucalyptus saligna	Firewood, civil construction (shores), sawmilling/lamination, posts/stakes/posts, cellulose and paper, furniture, structures, crates, charcoal
Eucalyptus urophylla	Firewood, charcoal, civil construction (shores), sawmilling/lamination, posts/stakes/posts, Flowers for honey production

Source: (Ferreira, 1979; CABI, 2019a; b; Embrapa, 2022)

There is significant interest in natural products for the development of new products for medical, agrochemical, and cosmetics applications. This demand has increased due to the need for safer raw materials. Additionally, the demand also responds to the rise in cases of microbial resistance and the emergence of pests and diseases without known control measures. Because of these challenges, the essential oils (EOs) market has grown considerably in recent years (Bizzo & Rezende, 2022), particularly essential oils from eucalyptus.

According to ISO 9235 of the International Organization for Standardization (ISO 9235, 2021), "essential oil is a product obtained from natural raw plant material by steam distillation, by mechanical processes from the epicarp of citrus fruits, or by dry distillation after the separation of the aqueous phase - if present - by physical processes." It is important to complement this definition by stating that aromatic products obtained by other extraction techniques, such as solvents, waxes, fats, supercritical fluids, headspace techniques, or any other means are not considered essential oils and have other designations as described in the same technical standard (Bizzo & Rezende, 2022). The extraction of *Eucalyptus* oil is carried out by hydrodistillation, thus making it an essential oil.

Essential oils are volatile, lipophilic substances originating from the secondary metabolism, composed of bioactive volatiles, in which terpenes are the largest group of components, classified according to their number of carbon atoms as monoterpenes, sesquiterpenes and diterpenes (Dhakad *et al.*, 2018; Koyama & Heinbockel, 2020). In plants, volatile terpene roles are not fully understood, although they have several functions highlighted. EOs contribute to attracting pollinators and seed dispersers, serve as a defence mechanism against phytopathogenic organisms, and exhibit allelopathic effects, influencing the growth and development of neighbouring plants. These multifaceted roles underscore their ecological and industrial significance (Zeroual *et al.*, 2021).

The constituents of Eucalypt oil are predominantly volatile terpenes and aromatic compounds (Aldoghaim *et al.*, 2018). Paul *et al.* (2020) reported the presence of terpenes, mainly monoterpenes (camphene, isocamphene, p-cymene, fenchone, fenchol, camphor, isoborneol, and borneol), preserved in amber from the late Oligocene, showing that the synthesis mechanism of these constituents evolved in the Cenozoic Era. Terpenes represent the largest group of secondary compounds. They are classified by the number of isoprene units they possess, synthesized in the cytoplasm and/or plastids of plant cells from the mevalonic acid (MEV) pathway in the cytosol and the methylerythritol phosphate (MEP) pathway in the chloroplast (Taiz *et al.*, 2017).

Depending on the species, essential oils can be produced in different parts of plants, such as flowers, leaves, stems, roots, fruits, and secretory structures, where they are also stored (Barbosa *et al.*, 2016). Eucalypt essential oils are mainly produced and stored in leaves (Filomeno *et al.*, 2016). Oil cavities are characteristic structures in Myrtaceae genera (Al-Edany & Al-Saadi, 2012), with variable distribution and size (Döll-Boscardin *et al.*, 2010).

The chemical composition, yield, and effectiveness of essential oils vary between and within species (Mugao, 2024). They are influenced by both endogenous and exogenous factors. Endogenous factors include plant characteristics such as age, density, plant part used, and genotype, which directly affect the synthesis and chemical variation of essential oils. Exogenous factors include environmental variables like light intensity, temperature, water availability, altitude, latitude, soil composition, extraction method, and storage (Mugao, 2024). The combination of these factors determines the final quality and effectiveness of the oil.

Eucalypt essential oils (EOs) are classified into medicinal, industrial, and perfumery categories based on specific constituents. They are used in the pharmaceutical and food industries, for therapeutic activities, and serve as raw materials for producing cosmetics, perfumes, cleaning products, insecticides, and herbicides. They are easily biodegradable, allowing their use in public places with extensive exposure, such as schools and hospitals (Dhakad *et al.*, 2018). EO production also enables greater profitability for eucalyptus, primarily used for wood and cellulose exploration, where the leaves are discarded (Filomeno *et al.*, 2016).

Some factors hinder the use of essential oils in commercial products, such as their standardization. Differences in the composition of oils from plants of the same species are observed depending on biotic and abiotic factors such as climatic conditions, light, soil type and conditions, agronomic management, plant phenological stage, in addition to the drying methods, extraction, and storage conditions used (Warnke *et al.*, 2009; Barbosa *et al.*, 2016; Bett *et al.*, 2016; Salem *et al.*, 2018). These varying conditions, combined with the genetic background of plants, can influence the activation or inhibition of metabolic pathways in aromatic plants (Knezevic *et al.*, 2016). Consequently, biological activities may also vary as they depend on chemical composition (Barbosa *et al.*, 2016). All these factors should be considered when seeking specific constituents. Two other factors that complicate using EOs in commercial products are the relatively rapid evaporation or degradation, which reduces effectiveness (Pavela, 2015).

Terpene biosynthesis in plants

Terpenes are present in almost all plants and they represent the largest and most diverse class of plant secondary metabolites. Terpenes volatiles are found in two terpene classes, monoterpenes and sesquiterpenes (Aqeel *et al.*, 2023), which can have several important physiological roles in plants, like defence against herbivory, attraction of mutualists such as pollinators, disease resistance, plant-plant communication, antioxidants, etc. (Butler *et al.,* 2018; Boncan *et al.*, 2020; Rosenkranz *et al.*, 2021). In general, stresses may change terpene plant composition and emission rates (Copolovici & Niinemets, 2016) and their profile can even vary within species and among individual plants (Kopaczyka *et al.*, 2020). Terpenes composition in *Eucalyptus camaldulensis* Dehnh., which has the largest range of distribution worldwide, both latitudinally and longitudinally, is influenced by environmental variables, mainly favouring the 1,8-cineole chemotype in arid locations (Bustos-Segura *et al.*, 2017). Significant changes in essential oil relative composition were also found in *E. camaldulensis* (Leicach *et al.*, 2010) and *E. globulus* (Queiroz *et al.*, 2017) submitted to drought. Terpenes composition in eucalyptus may also change with plant age (Shiferaw *et al.*, 2019).

Terpene synthesis is controlled by the terpene synthase gene family, which is highly diversified throughout the plant kingdom (Butler *et al.*, 2018). The biosynthesis of volatile organic compounds (VOCs) such as terpenes is limited by the enzymes involved in the process and the amount of substrate available for their functioning. Some enzymes require specific substrates, while others can synthesize various products from a single substrate (Vattekkatte *et al.*, 2018). Analyzing the genomes of two eucalyptus species (*E. globulus* and *E. grandis*), Külheim *et al.* (2015) confirmed that this diversity of terpenes is partially attributable to the largest family of terpene synthase (TPS) genes ever described.

Terpene synthase enzymes synthesize terpenes from isopentenyl diphosphate (IPP) and dimethylallyl diphosphate (DMAPP), which originate from the mevalonic acid (MEV) pathway in the cytosol and the methylerythritol phosphate (MEP) pathway in the plastids (Butler *et al.*, 2018). The synthesis of monoterpenes occurs in plastids (via methylerythritol 4-phosphate - MEP) from D-glyceraldehyde-3-phosphate pyruvate, while sesquiterpenes are synthesized in the cytosol (via mevalonate - MVA) from acetyl-CoA (Rajčević *et al.*, 2019), as illustrated in Fig. 1. In several plants, the two enzymes involved in the initial steps of the MEP pathway have been shown to influence the foliar yield of terpenes (Xu *et al.*, 2019). However, according to results obtained by Külheim *et al.* (2015), the foliar concentration of monoterpenes in eucalyptus appears to be influenced by the two final steps of the MEP pathway. For sesquiterpenes in the MVA pathway, the metabolite flow seems influenced by 3-hydroxy-3-methylglutaryl-CoA synthase – HMGS (Külheim *et al.*, 2015).

Several factors influence the ratio of mono- and sesquiterpenes in leaves, such as substrate availability for geranyl pyrophosphate synthase (GPPS) in the chloroplast and for farnesyl pyrophosphate synthase (FPPS) in the cytosol. Both enzymes use IPP (isopentenyl pyrophosphate) and DMAPP (dimethylallyl pyrophosphate) in different proportions (Bouvier *et al.*, 2000; Külheim *et al.*, 2015; Abdoul-Latif *et al.*, 2023). IPP and DMAPP react to produce geranyl pyrophosphate (GPP), serving as a precursor to monoterpenes. When GPP interacts with an additional IPP molecule, it forms farnesyl pyrophosphate (FPP), a sesquiterpene precursor. Similarly, the reaction of FPP with a third IPP molecule results in geranylgeranyl pyrophosphate (GGPP), which acts as a precursor for diterpenes (Abdoul-Latif *et al.*, 2023). Typically, oxygenated monoterpenes predominate in the composition of essential oils (Dhifi *et al.*, 2016), however, there are plants in which non-oxygenated terpenes are more abundant.

Biological activities of eucalyptus essential oils

Essential oils are increasingly recognized and utilized for numerous purposes across different sectors. Their lipophilic nature allows interactions with the cell plasma membrane, making it permeable. Moreover, they can depolarize the mitochondrial membrane, rendering it permeable and potentially leading to toxicity (Gautam *et al.*, 2014; Abdoul-Latif *et al.*, 2023). Another relevant point is that terpenes can easily traverse cell

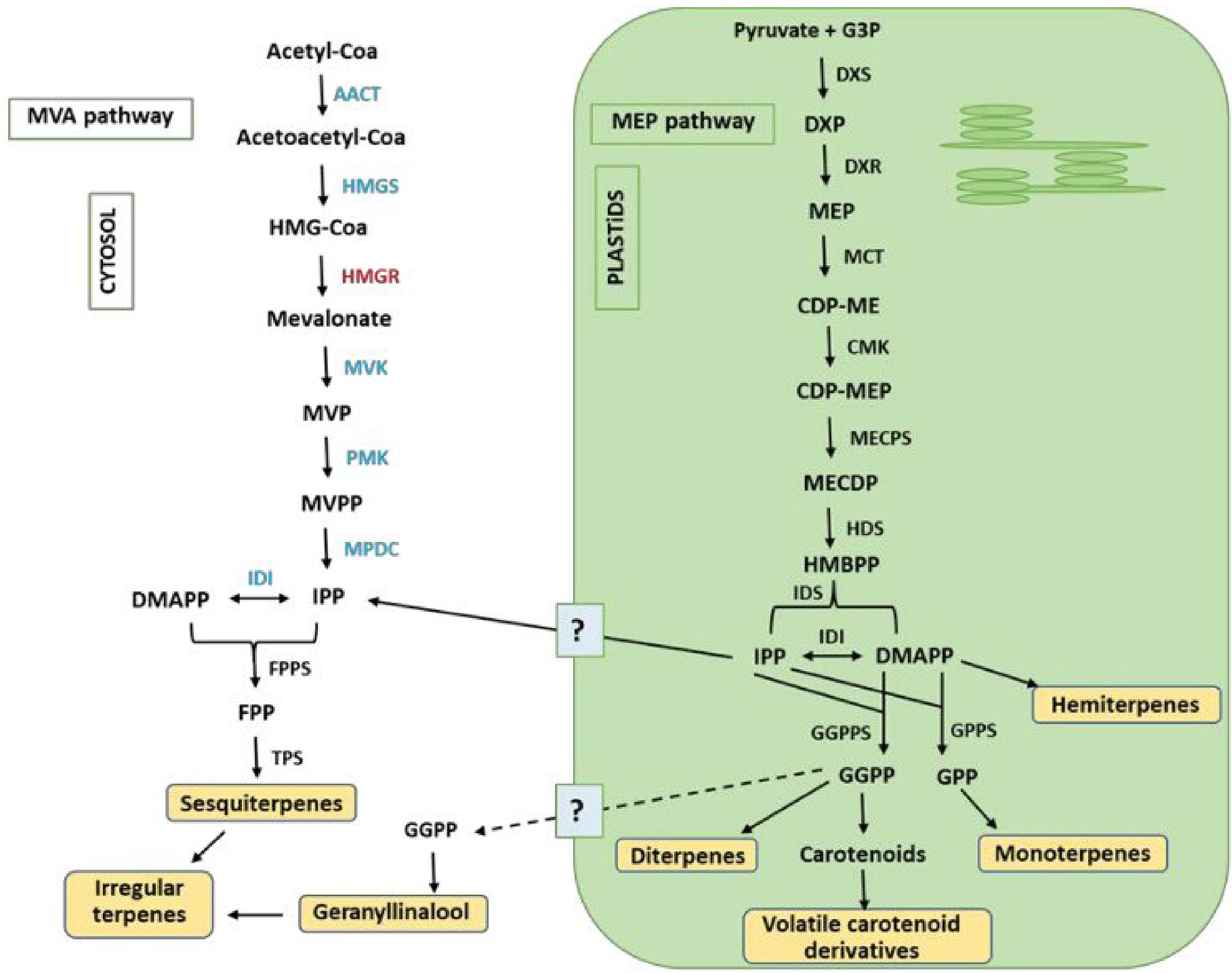

Figure 1. Synthesis of volatile terpenes (highlighted in yellow) through the mevalonate (MVA) pathway in the cytosol and the methylerythritol 4-phosphate (MEP) pathway in the plastid. The MVA pathway gives rise to sesquiterpenes, while the MEP pathway gives rise to monoterpenes. There is the export of isopentenyl pyrophosphate (IPP) from the plastid to the cytosol, with solid arrows indicating well-established steps and the dashed arrow representing hypothetical reactions. Enzymes in blue are located in the peroxisome, and those in red are in the endoplasmic reticulum. Abbreviations: AACT, acetyl-CoA acetyltransferase; HMGS, HMG-CoA synthase; HMG-CoA, hydroxymethylglutaryl-CoA; HMGR, HMG-CoA reductase; MVK, mevalonate kinase; MVP, mevalonate 5-phosphate; PMK, phosphomevalonate kinase; MVPP, mevalonate 5-pyrophosphate; MPDC, mevalonate diphosphate decarboxylase; IPP, isopentenyl pyrophosphate; IDI, isopentenyl pyrophosphate isomerase; DMAPP, dimethylallyl pyrophosphate; FPPS, FPP synthase; FPP, farnesyl pyrophosphate; TPS, terpene synthase; G3P, glyceraldehyde 3-phosphate; DXS, DXP synthase; DXP, 1-deoxy-D-xylulose 5-phosphate; DXR, 1-deoxy-D-xylulose 5-phosphate reductoisomerase; MCT, 2-C-methyl-D-erythritol 4-phosphate cytidylyltransferase; CDP-ME, 4-diphosphocytidyl-2-C-methyl-D-erythritol; CMK, 4-(cytidine 5'-diphospho)-2-C-methyl-D-erythritol kinase; CDP-MEP, CDPME 2-phosphate; MECPS, MECPD synthase; MECDP, 2-C-methyl-D-erythritol 2,4-cyclodiphosphate; HDS, 4-hydroxy-3-methylbut-2-en-1-yl diphosphate synthase; HMBPP, (E)-4-hydroxy-3-methylbut-2-en-1-yl diphosphate; IDS, isopentenyl diphosphate synthase; GGPPS, GGPP synthase; GGPP, geranylgeranyl pyrophosphate; GPPS, GPPS synthase; GPP, geranyl pyrophosphate. Source: Adapted from Dudareva *et al.* (2013).

membranes due to their low molecular weight, thereby inducing biological activities such as antimicrobial and antioxidant effects (Al-Radadi, 2022). Defining the modes and mechanisms of action determining the efficacy of essential oils is challenging due to their complex and variable composition, requiring further studies.

Many studies focus on the use of EOs as potential antimicrobials because conventional chemicals typically lose their efficacy due to misuse, the development of microbial resistance, or the emergence of microorganisms that require new means of control. In addition to the resistance mechanisms developed by microorganisms, there is the risk of the resistance factor being transmitted to pathogenic descendants (Salem *et al.*, 2018).

The increased use of EOs in agricultural pest management is also justified by changes in pesticide market regulations in the European Union (EU) (Directive 2009/128/EC), which mandate the implementation of Integrated Pest Management (IPM) and the sustainable use of pesticides, especially non-synthetic ones, for weed control (Verdeguer *et al.*, 2020b). A comprehensive review of the bioherbicidal potential of EOs from various weed species was conducted by Verdeguer *et al.* (2020b). These authors highlighted two challenges for evaluating EOs *in vivo*: they must be mixed with emulsifiers and not with water, making the type of emulsifier another factor to be tested, and rapid volatilization requires appropriate formulations, with microencapsulation and nanoemulsion being the most commonly used for EOs (Vinceković *et al.*, 2017).

Tab. 2 shows the biological activities of eucalyptus EOs published in the literature. The eucalyptus oils have a large range of bioactivity probably because of their diverse composition. The bioactivities cover from agriculture applications to the control of human pathogens. Other eucalyptus species from which essential oil is extracted for medicinal use include *E. maidenii* F. Muell, *E. bicostata* Maiden, Blakely & Simmond, *E. sideroxylon* A. Cunn. ex Woolls, *E. cinerea* F. Muell. ex Benth., *E. leucoxylon* F. Muell., and *E. tereticornis* Sm. (Mieres-Castro *et al.*, 2021).

Formulations that yield satisfactory results have to meet environmental and safety concerns. Pant *et al.* (2014) prepared a nanoemulsion using aqueous filtrates of *Pongamia glabra* Vent. and *Jatropha curcas* L. left after biodiesel oil extraction to enhance the activity of *Eucalyptus globulus* Labill. oil in controlling *Tribolium castaneum* (Herbst), a pest of stored grains. The product was effective in control, with karanjin, phorbol esters, and eucalyptol being the main constituents responsible for the observed insecticidal effect. It is worth noting that such products improve the performance of EOs and can be used on food grains, not polluting the environment and expanding the range of pesticide products, reducing resistance risks.

Table 2. Biological effects of the essential oils of different *Eucalyptus* species, described in the literature.

Effect	Reference
Eucalyptus camaldulensis Dehnh	
Activity against gram-positive and gram-negative bacteria	(Salem *et al.*, 2015)
Inhibition of the growth of fungi *Alternaria alternata* and *Chaetomium globosum* in commercial wood	(Salem *et al.*, 2016)
Antibacterial against *Bacillus subtilis*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Yersinia enterocolitica*, *Salmonella Paratyphi*, *Salmonella typhi*, *Salmonella typhimurium*, *Vibrio vulnificus*, *Escherichia coli*, and *Pseudomonas aeruginosa*	(Debbarma *et al.*, 2013)
Repellent against *Sitophilus zeamais*	(Karemu *et al.*, 2013)
Antibacterial against *Staphylococcus aureus*, *Bacillus subtilis* and *Escherichia coli* Antifungal against *Aspergillus niger* and *Rhizopus solani* Antioxidant for linoleic acid	(Ghaffar *et al.*, 2015)
Insecticide against *Ectomielois ceratoniae*	(Jemâa *et al.*, 2013)
Insecticide against *Callosobruchus maculatus*, *Sitophilus oryzae* and *Tribolium castaneum*	(Negahban & Moharramipour, 2007)
Antibacterial against *Acinetobacter baumannii* isolates	(Knezevic *et al.*, 2016)
Inhibition of germination and growth of invasive species *Amaranthus hybridus* L. and *Portulaca oleracea* L.	(Verdeguer *et al.*, 2009)
Antibacterial Against *Escherichia coli* ATCC 25922, *Staphylococcus aureus* ATCC 29213 and *Enterococcus faecalis* ATCC 29212 Moderate antibacterial effect against *Pseudomonas aeruginosa* ATCC 27853	(Tine *et al.*, 2022)

Table 2. Cont.

Effect	Reference
Antibacterial against *Bacillus cereus*, *Citrobacter diversus, Klebsiella oxytoca*, *Klebsiella pneumoniae*, *Proteus vulgaris*, *Shigella flexneri* Antifungal against *Aspergillus clavatus*, *Candida albicans*, *Cladosporium cladosporioides*, *Lenzites sulphureus*, *Myrothecium verrucaria*, *Penicillium citrinum*, *Phanerochaete chrysosporium*, *Phaeolus schweintizii*, *Trametes versicolor*, *Trichoderma viride* Acaricidal against *Varroa destructor* Insecticidal against *Aedes aegypti*, *Aedes albopictus*, *Atta sexdens rubropilosa*, *Ephestia cautela*, *Ephestia kuehniella*, *Pediculus humanus capitis*, *Thyrinteina arnobia*	(Barbosa *et al.*, 2016)
Herbicide against *Erigeron bonariensis* L.	(Verdeguer *et al.*, 2020a)
Eucalyptus dunnii Maiden	
Repellent and insecticide against *Sitophilus zeamais*	(Mossi *et al.*, 2011)
Insecticide against *Aedes aegypti*, *Blattella germanica*, *Pediculus humanus capitis*	(Barbosa *et al.*, 2016)
Eucalyptus exserta F.Muell	
Inhibition of gram-negative bacteria *Salmonella enteritidis*	(Ambrosio *et al.*, 2017)
Fumigant against *Tribolium castaneum*	(Li & Xu, 2012)
Fungicide against *Aspergillus flavus* and *Aspergillus niger*	(Oanh & Giang, 2017)
Eucalyptus globulus Labill	
Activity against larvae and pupae of *Musca domestica*	(Kumar *et al.*, 2012)
Termiticidal activity against termites *Odontotermes assamensis*	(Pandey *et al.*, 2012)
Repellent against *Sitophilus zeamais*	(Karemu *et al.*, 2013)
Potential control of dental plaque by *Streptococcus mutans*	(Goldbeck *et al.*, 2014)
Antibacterial against *Staphylococcus aureus*, *Bacillus subtilis* and *Escherichia coli* Antifungal against *Aspergillus niger* and *Rhizopus solani* Antioxidant for linoleic acid	(Ghaffar *et al.*, 2015)
Insecticide and ovicide against *Pediculus humanus capitis*	(Yones *et al.*, 2016)
Antibacterial against *Staphylococcus aureus*, *Streptococcus pyogenes*, *Staphylococcus epidermidis*, *Salmonella typhi*, *Escherichia coli*, *Shigella* spp. And *Pseudomonas aeruginosa* Antifungal against *Trichophyton* spp1 and *Aspergillus* spp	(Mekonnen *et al.*, 2016)
Antioxidant – radical-scavenging properties and ability to inhibit lipid peroxidation Antibacterial – synergistic effect between the oil and conventional antibiotics against *Acinetobacter baumannii*	(Luís *et al.*, 2016)
Antibacterial against *Staphylococcus aureus*, *Escherichia coli* and *Pseudomonas aeruginosa*	(Pombal *et al.*, 2014)
Antibacterial against *Staphylococcus aureus* Wound healing in rats	(Sugumar *et al.*, 2014)
Repellent and insecticide against *Sitophilus zeamais*	(Mossi *et al.*, 2011)
Antimicrobial against multidrug-resistant bacteria	(Mulyaningsih *et al.*, 2011)
Strong antimicrobial, especially against *Streptococcus pyogenes*, *Escherichia coli*, *Candida albicans*, *Staphylococcus aureus*, *Acinetobacter baumannii* and *Klebsiella pneumoniae*	(Damjanović-Vratnica *et al.*, 2011)
Antibacterial against gram-negative periodontopathogenic bacteria, mainly *Fusobacterium nucleatum* ATCC25586 and *Porphyromonas gingivalis* ATCC33277	(Harkat-Madouri *et al.*, 2015)
Insecticide against *Triboliu confusum* (oil extracted from young leaves had a better effect compared to oil from mature leaves)	(Russo *et al.*, 2015)
Inhibition of germination and development of invasive plants *Amaranthus blitoides* and *Cynodon dactylon*	(Rassaeifar *et al.*, 2013)
Antioxidant through the reduction of metal ions that perpetuate the formation of free radicals, induce lipid peroxidation, and consequently disrupt the homeostatic balance of human cells	(Salem *et al.*, 2018)

Table 2. Cont.

Effect	Reference
Antibacterial against *Bacillus cereus*, *Citrobacter* diversus, *Enterococcus faecalis*, *Fusobacterium nucleatum*, *Klebsiella oxytoca*, *Klebsiella pneumoniae*, *Porphyromonas gingivalis*, *Pseudomonas fluorescens*, *Salmonella paratyphi*, *Salmonella typhimurium*, *Staphylococcus intermedius*, *Staphylococcus sciuri*, *Staphylococcus warneri* Antifungal against *Aspergillus flavus*, *Aspergillus parasiticus*, *Aspergillus* spp., *Candida albicans*, *Fusarium oxysporum*, *Mucor* spp., *Penicillium digitatum*, *Rhizopus nigricans*, *Saccharomyces cerevisiae* Acaricidal against *Boophilus microplus* Insecticidal against *Aedes aegypti*, *Lutzomyia longipalpis*, *Sitophilus oryzae*, *Tribolium castaneum*	(Barbosa *et al.*, 2016)
Inhibition of growth of gram-positive against *Sthaphylococcus aureus*, gram-negative *Proteus vulgaris* and *Escherichia coli*, and the fungus *Candida albicans*.	(Mota *et al.*, 2015)
Anti-influenza A activity	(Vimalanathan & Hudson, 2014)
Acaricidal and repellent activity against *Rhipicephalus bursa*	(Madreseh-Ghahfarokhi *et al.*, 2019)
Activates Complement Receptor-Mediated Phagocytosis and Stimulates Podosome Formation in Human Monocyte-Derived Macrophages	Zonfrillo *et al.*, 2022
Eucalyptus grandis W.Hill ex Maiden	
Antibacterial against e *Escherichia coli* (ATCC 8739), *Psuedomonas aeruginosa* (ATCC 19582), *Staphylococcus aureus* (ATCC 6538), *Streptococcus faecalis* (ATCC 29212), *Bacillus cereus* (ATCC 10702), *Bacillus Pumilus* (ATCC 14884), *Psuedomonas aeruginosa* (ATCC 7700), *Enterobacter cloacae* (ATCC 13047), *Klebsiella pneumonia* (ATCC 10031), *Bacillus subtilis* (KZN), *Shigella flexineri* (KZN), *Salmonella* spp. (KZN), *Staphylococcus epidermidis* (KZN) and *Enterococcus faecalis* (KZN) Antibacterial against antibiotic-resistant species: *Staphylococcus aureus* (P12702/ P12763/ P12724/ B10808), *Streptococcus viridans* (S17141), *Klebsiella* spp. (S17302) and *Klebsiella pneumonia* (S17298)	(Sewanu *et al.*, 2012)
Antibacterial against *Staphylococcus aureus* ATCC6538, *Escherichia coli* ATCC8739, *Escherichia coli* 0:158 and *Salmonella choleraeseus* ATCC10708	(Estanislau *et al.*, 2001)
Larvicidal against *Aedes aegypti*	(Gallon *et al.*, 2020)
Antifungal against *Aspergillus clavatus*, *Aspergillus niger*, *Chaetomium globosum*, *Cladosporium cladosporioides*, *Lenzites sulphureus*, *Myrothecium verrucaria*, *Penicillium citrinum*, *Phaeolus schweintizii*, *Phanerochaete chrysosporium*, *Trametes versicolor*, *Trichoderma viride* Insecticidal gainst *Aedes aegypti*, *Atta sexdens rubropilosa*, *Blattella gainsta*, *Pediculus humanus capitis*, *Thyrinteina arnobia*	(Barbosa *et al.*, 2016)
Eucalyptus pellita F.Muell	
Antibacterial against strains of *Pseudomonas aeruginosa*, *Escherichia coli*, *Staphylococcus aureus* and *Bacillus subtilis*	(Proenza *et al.*, 2013)
Antibacterial against *Streptococcus sobrinus* and *Streptococcus mutans*, causative agents of dental caries	(Kartiko *et al.*, 2021)
Eucalyptus resinifera Sm	
Fumigant and larvicidal against *Aedes aegypti*	(Lucia *et al.*, 2012)
Insecticidal against *Rhyzopertha dominica* (more toxic to insects than the commercial insecticide pirimiphos-methyl)	(Filomeno *et al.*, 2020)
Fumigant and repellent against *Hypothenemus hampei*	(Reyes *et al.*, 2019)
Insecticidal against *Haematobia irritans*	(Barbosa *et al.*, 2016)
Eucalyptus saligna Sm	
Repellent against *Sitophilus zeamais*	(Karemu *et al.*, 2013)
Repellent and insecticidal against *Sitophilus zeamais*	(Mossi *et al.*, 2011)
Antimicrobial against bacteria *Staphylococcus aureus and Escherichia coli* and fungi *Candida albicans and Phytophthora cactorium*	(Sartorelli *et al.*, 2007)
Insecticidal and repellent against *Sitophilus zeamais* and *Tribolium confusum* in grain storage	(Tapondjou *et al.*, 2005)
Antibacterial against *Bacillus cereus*, *Bacillus subtilis*, *Citrobacter diversus*, *Klebsiella oxytoca*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Salmonella choleraesuis* Insecticidal against *Aedes aegypti*, *Atta sexdens rubropilosa*, *Pediculus humanus capitis*, *Thyrinteina arnobia*	(Barbosa *et al.*, 2016)

Table 2. Cont.

Effect	Reference
Potential antimicrobial against gram-positive bacterium *Staphylococcus aureus* and yeast *Candida albicans* Cytotoxicity against tumor cell lines Calu-3 and 3T3	(Saulle, 2018)
Antibacterial against *Staphylococcus aureus* ATCC6538, *Escherichia coli* ATCC8739, *Escherichia coli* 0:158 and *Salmonella choleraeseus* ATCC10708	(Estanislau *et al.*, 2001)
Fumigant and repellent against pest insects *Callosobruchus chinensis* and *Sitophilus zeamais*	(Bett *et al.*, 2013)
Insecticidal and repellent against stored grain pests (*Tribolium castaneum*, *Acanthoscelides obtectus*, *Sitotroga cerealella* and *Sitophilus zeamais*)	(Bett *et al.*, 2016)
Eucalyptus urophylla S.T.Blake	
Larvicide and repellent against *Culex quinquefasciatus*, the filariasis vector mosquito	(Pujiarti & Kasmudjo, 2016)
Antibacterial against *Bacillus subtilis*, *Escherichia coli*, *Klebsiella oxytoca*, *Klebsiella pneumoniae* Antifungal against *Aspergillus clavatus*, *Aspergillus niger*, *Chaetomium globosum*, *Cladosporium cladosporioides*, *Lenzites sulphureus*, *Myrothecium verrucaria*, *Penicillium citrinum*, *Phanerochaete chrysosporium*, *Phaeolus schweintizii*, *Trametes versicolor*, *Trichoderma viride* Insecticidal against Atta *sexdens rubropilosa*, *Thyrinteina arnobia* Herbicidal against *Lactuca sativa*	(Barbosa *et al.*, 2016)

Eucalyptus essential oil was trapped within the micro-nanostructures of a polydimethylsiloxane (PDMS) substrate, which increased significantly the hydrophobicity (Hidouri *et al.*, 2024). The authors demonstrated the antibacterial ability of these superhydrophobic surfaces to inhibit the growth of *Escherichia coli* (Migula) Castellani & Chalmers and *Bacillus cereus* Frankland & Frankland bacterial colonies and biofilms.

Due to the complexity of EOs composition, relating observed effects to only one constituent is still a challenging task, as additive, synergistic, or antagonistic effects may occur with their combinations (Yap *et al.*, 2014; Filomeno *et al.*, 2020; Verdeguer *et al.*, 2020b). While some researchers associate the fumigant effect of eucalyptus EOs against grain pests with its eucalyptol content (Aref *et al.*, 2015; Hamdi *et al.*, 2015), Filomeno *et al.* (2020) found that eucalyptus EOs with approximately 70% eucalyptol showed intermediate mortality, suggesting that other constituents may promote antagonistic effects. When evaluating the antibacterial efficacy of eucalyptus EOs compared to eucalyptol, its dominant constituent, Hendry *et al.* (2009) found better results with the oil, suggesting that other minor constituents also contribute to the final objective. A similar situation was observed in other studies when testing the effect of *Eucalyptus resinifera* EO and its main active ingredients against the pests *Rhyzopertha dominica* Frabricius (Filomeno *et al.*, 2020) and *Hypothenemus hampei* Ferrari (Reyes *et al.*, 2019).

It has been suggested a possible synergistic effect between eucalyptol and p-cymene in increasing the antibacterial activity of EOs, additive and synergistic effects between eucalyptol and aromadendrene against methicillin-resistant *Staphylococcus aureus* (Salem *et al.*, 2018), and additive effects between eucalyptol and p-cymene against *Rhyzopertha dominica* (Filomeno *et al.*, 2020). A wide range of binary mixtures of components present in EOs was tested to assess the effect (antagonism, synergism, or no effect) against larvae of *Spodoptera littoralis* (Pavela, 2014).

EOs are used in the composition of commercial products, such as some herbicides available in the North American market, such as Matratec (50% clove oil), WeedZap (45% clove oil + 45% cinnamon oil), and GreenMatch EX (50% lemongrass oil) (Verdeguer *et al.*, 2020b). They can also be combined to develop new products, as demonstrated by Golestani *et al.* (2015), who formulated two phytomedicines from different concentrations of four EOs (*Eucalyptus globulus*, *Dianthus caryophyllus* L., *Mentha piperita* L., and *Thymus vulgaris* L.) against *Escherichia* *coli* O157:H7. These formulations were tested, showing superior antibacterial effects compared to a commercially available phytomedicine with *Thymus vulgaris* essential oil. Another possibility is the combination of EOs with existing products to enhance results, as mentioned by Luís *et al.* (2016) when observing a synergistic effect between commercial antibiotics and *Eucalyptus globulus* EO against *Acinetobacter baumannii* Bouvet and Grimont, a multi-resistant opportunistic pathogen typically associated with hospital infections. Knezevic *et al.* (2016) also reported *in vitro* synergistic effects of antibiotics ciprofloxacin, gentamicin, and polymyxin B with essential oils of *Eucalyptus camaldulensis* against multi-resistant *A. baumannii*.

The application method of EOs and their active compounds can also lead to distinct results, as Filomeno *et al.* (2020) mentioned. When they applied eucalyptol alone against *Rhyzopertha dominica* Fabricius adults, they obtained a better response as a fumigant (97.5% mortality) than when applied topically (32.5% mortality).

There are numerous applications for EOs, such as potential plant biostimulants (Steffen *et al.*, 2010; Praça, 2019). However, these effects are directly related to the constituents present in the oils. In other words, the results will also vary if there is variation in the necessary active compound within the same species. Knezevic *et al.* (2016) tested the antibacterial activity of two oils from *E. camaldulensis* produced in different regions of Montenegro against *Acinetobacter baumannii* and observed that one of the oils showed slightly higher activity than the other.

This knowledge about the activity of constituents and their different modes of action also allows an EO to be used for numerous purposes. Tab. 3 shows the activities of the components of eucalyptus EOs. It is interesting to observe that some components have several activities, while others have very little. This may be partly related to the number of studies focused on a component. For example, eucalyptol has several activities described in several reports, while only one is described for spathulenol. On the other hand, α-terpineol has several activities but is described in much fewer reports than eucalyptol. The number of studies on a component may also be related to the activity's potency and the component's abundance in the eucalyptus oil.

Various oils can be used for the same purpose as long as the necessary active compounds are present in the ideal proportion to perform these functions. For example, Lucia *et al.* (2012) studied the validation of models to estimate the fumigant and larvicidal activity of eucalyptus EOs against *Aedes aegypti* Linnaeus. They concluded that the larvicidal effect can be estimated based on the relative concentration of p-cymene and eucalyptol,

Table 3. Biological activities described in the literature for constituents of eucalyptus EOs.

Constituent	Effect	Reference
Eucalyptol	Antimicrobial Antibacterial Repellent against *Sitophilus zeamais* Mosquito repellency, antitumor properties in rats, anti-inflammatory and antibacterial activity Proven fumigant in various insect species (*Pediculus humanus capitis*, *Rhodnius prolixus*, *Musca domestica*, *Sitophilus oryzae*, *Tribolium castaneum*, *Rhzopertha dominica*, *Haematobia irritans*, *Blattella germanica* and *Aedes aegypti*) Termiticide against termites *Odontotermes assamensis* May inhibit viral replication of SARS-CoV-2 Attenuates viral pulmonary inflammatory responses Cross-protection against influenza virus	(Salem *et al.*, 2015) (Debbarma *et al.*, 2013) (Golestani *et al.*, 2015) (Karemu *et al.*, 2013) (Mekonnen *et al.*, 2016) (Mulyaningsih *et al.*, 2011) (Lucia *et al.*, 2012) (Alzogaray *et al.*, 2011) (Pandey *et al.*, 2012) (Li *et al.*, 2016) (Li *et al.*, 2017)
Spathulenol	Possible antioxidant activity	(Salem *et al.*, 2015)
α-Terpineol	Antibacterial against *Staphylococcus aureus* Cardiovascular and anti-hypertensive effects Antioxidant Antinociceptive activity Anti-ulcer activity Anticonvulsant and sedative activities Chemical enhancer for skin penetration Insecticide	(Salem *et al.*, 2015) (Khaleel *et al.*, 2018)

Table 3. Cont.

Constituent	Effect	Reference
p-Cymene	Antibacterial Termiticide against termites *Odontotermes assamensis* Fumigant against *Blattella germanica* (1st instar nymph) Industrial solvent in paints and varnishes and in the production of synthetic resins Anti-inflammatory activity	(Cantore *et al.*, 2009) (Fratini *et al.*, 2014) (Salem *et al.*, 2015) (Pandey *et al.*, 2012) (Alzogaray *et al.*, 2011) (Filomeno *et al.*, 2016) (Chen *et al.*, 2014) (Zhong *et al.*, 2013)
O – Cymene	Fungicide against *Botrytis cinerea*	(Camele *et al.*, 2012)
Limonene	Antibacterial Repellent against *Sitophilus zeamais*	(Cantore *et al.*, 2009) (Salem *et al.*, 2015) (Karemu *et al.*, 2013)
D-Limonene	Anticancer effect against colon cancer cells (LS174T) (Apoptosis via akt pathway inactivation)	(Jia *et al.*, 2013)
α-Pinene	Repellent against *Sitophilus zeamais* Antibacterial Termiticide against *Odontotermes assamensis* termites Fumigant against *Blattella germanica* (1st instar nymph) Capable of inhibiting respiratory and ion transport processes, compromising cellular integrity. Larvicide against *Aedes aegypti*	(Karemu *et al.*, 2013) (Cantore *et al.*, 2009) (Golestani *et al.*, 2015) (Mekonnen *et al.*, 2016) (Pandey *et al.*, 2012) (Alzogaray *et al.*, 2011) (Filomeno *et al.*, 2016) (Gallon *et al.*, 2020)
⍰-Pinene	Antibacterial Repellent against *Sitophilus zeamais* Capable of inhibiting respiratory and ion transport processes, compromising cellular integrity. Larvicide against *Aedes aegypti* Fungicide against *Botrytis cinerea*	(Cantore *et al.*, 2009) (Salem *et al.*, 2015) (Golestani *et al.*, 2015) (Karemu *et al.*, 2013) (Filomeno *et al.*, 2016) (Pavela, 2015) (Camele *et al.*, 2012)
4-terpineol	Anticancer activity through cell death and inhibition of aggressive tumor cell growth – Murine mesothelioma (AE17), melanoma cells (B16-F10), and fibroblasts (L929) Termiticide against termites *Odontotermes assamensis* Cytotoxic effect against cancer cells	(Greay *et al.*, 2010) (Pandey *et al.*, 2012) (Döll-Boscardin *et al.*, 2012)
Aromadendrene	Antibacterial	(Salem *et al.*, 2015) (Mulyaningsih *et al.*, 2011)
Geranyl acetate	Termiticide against *Odontotermes assamensis* Antibacterial	(Pandey *et al.*, 2012) (Cantore *et al.*, 2009)
Isoborneol	Termiticide against *Odontotermes assamensis*	(Pandey *et al.*, 2012)
α-Phellandrene	Fungicide against *Botrytis cinérea*	(Camele *et al.*, 2012)
Camphene	Fungicide against *Botrytis cinérea*	(Camele *et al.*, 2012)
⍰-Myrcene	Food additive Analgesic, sedative, antidiabetic, antioxidant, anti-inflammatory, antibacterial, and anticancer effects	(Surendran *et al.*, 2021)
Viridiflorol	Cytotoxic and apoptotic activity in three different cancer cell lines (brain, breast, and lung) Potential anti-arthritic, antinociceptive, and anti-hyperalgesic properties	(Akiel *et al.*, 2022) (Balsalobre *et al.*, 2023)

while insecticidal activity typically occurs due to a large amount of eucalyptol. Additionally, the authors noted that an oil with a high insecticidal effect usually promotes lower larvicidal activity.

Results obtained over a long period showed that the use of eucalyptol allowed for a 36% reduction in the use of steroids in severe asthmatic patients. Other studies also highlight the efficacy of eucalyptol in improving patients with chronic respiratory conditions, demonstrating its anti-inflammatory activity (Asif *et al.*, 2020), in addition to mucolytic and bronchodilator properties (Juergens *et al.*, 2020), which explains the presence of eucalyptol in Vick VapoRub™, a widely used commercial product as a nasal decongestant (Asif *et al.*, 2020). Other commercial medications based on eucalyptol and other constituents of eucalyptus essential oil are also available on the market and have garnered attention for their respiratory system benefits. Examples include Myrtol® (a 300 mg capsule containing at least 75 mg of eucalyptol, 75 mg of limonene, and 20 mg of α-pinene), which is sold commercially as GeloMyrtol® and GeloMyrtol forte® (Chandorkar *et al.*, 2021).

The use of eucalyptus oil, both in its complete form and isolated constituents, has shown potential in antiviral therapies (Schnitzler, 2019; Reichling, 2021), with positive impacts on the treatment of colds, asthma, and bronchiolitis through vapour inhalation (Kim, 2021; Panikar *et al.*, 2021).

Recent research has also been conducted using eucalyptus essential oils and constituents such as eucalyptol and jensenone in studies related to the treatment of COVID-19, with exciting and promising preliminary results (Asif *et al.*, 2020; Sharma & Kaur, 2020; Panyod *et al.*, 2020; Abbass, 2020; Panikar *et al.*, 2021). A significant interaction was observed between bioactive constituents found in eucalyptus essential oil and the Mpro protease enzyme of SARS-CoV-2. This enzyme is crucial for viral replication and transcription, and the results suggest that eucalyptus essential oil or certain monoterpenes like eucalyptol may have an inhibitory effect on the coronavirus (Silva *et al.*, 2020; Fitriani *et al.*, unpub. data; Panikar *et al.*, 2021).

Mieres-Castro *et al.* (2021) suggest that the virucidal effect of essential oil and its constituents is related to modifications in the viral envelope and associated structures, such as glycoproteins, which are essential for viral adsorption and entry into host cells. Furthermore, they emphasize that some studies support this mechanism by demonstrating the inhibition of critical viral enzymes.

Although many benefits have been reported from the mixture of oils and their constituents, antagonistic effects can also be observed and should be equally documented. According to Gibbs (2019), EOs containing pinene and linalool can cause respiratory complications, such as rhinitis and seasonal asthma, in allergic individuals. Verdeguer *et al.* (2020b) added that allergic individuals or those sensitive to a constituent may experience reactions such as contact dermatitis after contact with the EOs. The use of essential oils and their constituents for specific situations still provides preliminary information and should be evaluated on a case-by-case basis through detailed research to establish their efficacy, active ingredients, and safe doses for each purpose, particularly concerning human health.

The Brazilian essential oil market

There are several ISO standards related to the technical specifications of essential oils for each botanical species, analysis methods, and labelling for commercialization. These technical specifications aim to standardize products within tolerance ranges (Bizzo & Rezende, 2022). However, when searching for information on the essential oils market, it is expected to find other aromatic extracts obtained by solvents or any other product that does not fit into the category, making analysis and comparison of information challenging (Bizzo & Rezende, 2022).

In Brazil, the classification of oils is done through a set of numerical codes originating from three nomenclatures: global product nomenclatures (Harmonized System – HS), Mercosur (Common Nomenclature of Mercosur – NCM), which complements the first, and Brazil (National Classification of Economic Activities – CNAE), which complements the previous ones and classifies oils into three categories (Orange Essential Oils, Essential Oils of other citruses except orange, and other Essential Oils), making it difficult to collect specific information about eucalyptus EO production (Bizzo & Rezende, 2022).

According to 2021 International Trade Centre Map (ITC) data, Brazil was at the top of the ranking when it comes to the export of essential oils (quantity) in the international market, followed by India, the United States, China, and the United Kingdom. The main destinations for Brazilian oils are the United States, the Netherlands, Germany, China, and India. But in general, the countries that lead world imports in volume are the United States, Burkina Faso, Germany, the United Kingdom, and France. Regarding export values, China rises to the first position, and Brazil falls to the fifth, which can be explained by the variation in the prices of oils from the botanical species each country trades (ITC Trade Map, 2023).

The ITC Trade Map (2023) data includes, in addition to essential oils, all aromatic materials classified in position 3301 of the HS, which considers "essential oils (terpeneless or not), including so-called 'concretes' or 'absolutes'; resinoids; oleoresins of extraction; concentrated solutions of essential oils in fats, fixed oils, waxes or similar materials, obtained by treating flowers with fatty substances or by maceration; terpene residues resulting from the terpeneless of essential oils; aromatic distilled waters and aqueous solutions of essential oils." Thus, it is noted that the detailed study of the international market is complex because, in addition to the available information, including products not considered essential oils, *i.e.*, not falling under ISO 9235, many documents from specific agencies are not freely available.

Despite this complexity regarding the classification and obtaining of accurate and unified information from the global essential oils market, there was growth in this market after the pandemic (Pascuta & Vodnar, 2022), driven by increased consumer awareness of its benefits, leading manufacturers from various sectors to replace synthetic ingredients with natural ones, following the demand. It is a market with a forecasted growth of 8.6% (2023-2027). However, it is still well-segmented, represented mainly by companies such as KATO Flavors & Fragrances (KFF), Herbal Family, Robertet, Food Base Kft, Biolandes, A. Fakhry & Co., Lebermuth Inc., Givaudan SA, Sydney Essentials, Phoenix Aromas & Essential Oils LLC, Doterra Holdings LLC (Mordor Intelligence, 2023).

In Brazil, among the most exported essential oils, orange essential oil stands out due to the orange juice industry's strong production and export market, followed by citrus essential oils (except orange) and eucalyptus essential oil. Specifications about imported essential oils are more restricted due to the significant number of species within the "other essential oils" classification, but the most relevant essential oil is Japanese mint oil (*Mentha arvensis*), with others like eucalyptus, lemon, orange, and lavender also being significant. Much of this information can be obtained from the portal for free access to Brazil's foreign trade statistics – Comex Stat - https://comexstat.mdic.gov.br/pt/home.

By filtering only the essential oils data (HS code 3301.11.00 to 3301.29.90) in the "general export and import" category, it is possible to track transactions from 1997 to the present. Analyzing Fig. 2A-B, the quantities of essential oils exported in this period averaged 28 thousand tons, with the maximum reached in 2020 (36 thousand tons) and the minimum in 2000 (18 thousand tons). The received values increased until 2018, with declines in 2019, 2020, and 2021, reaching a peak in 2022 (USD 323 million). The average of imported essential oils in the same period was two thousand tons, with the smallest quantities and the highest values recorded in the last decade. The price of essential oils varies significantly according to the botanical species, quantitative and qualitative composition, availability in each country, and market dynamics.

Analyzing specifically eucalyptus EO (HS code 3301.29.19) (Fig. 3A-B), it is noted that after a decline in exports in 2012 and 2013, these numbers increased in the following period until reaching around 560 tons exported and eight million dollars in 2020, which was maintained with slight variation until 2022. As for importation, in the last decade, it has remained around 200 tons.

For EOs and their constituents to be used and commercialized *in natura* or incorporated into any formulation, they must comply with the current legislation of each country. If these products are exported, the regulations of the destination country must also be checked.

In Brazil, there is still no well-consolidated regulation regarding the use of EOs, and they must follow specific norms according to their established use, such as food additives, phytotherapies, medicines, and cosmetics; these norms should always be consulted as they may be updated (Bizzo & Rezende, 2022).

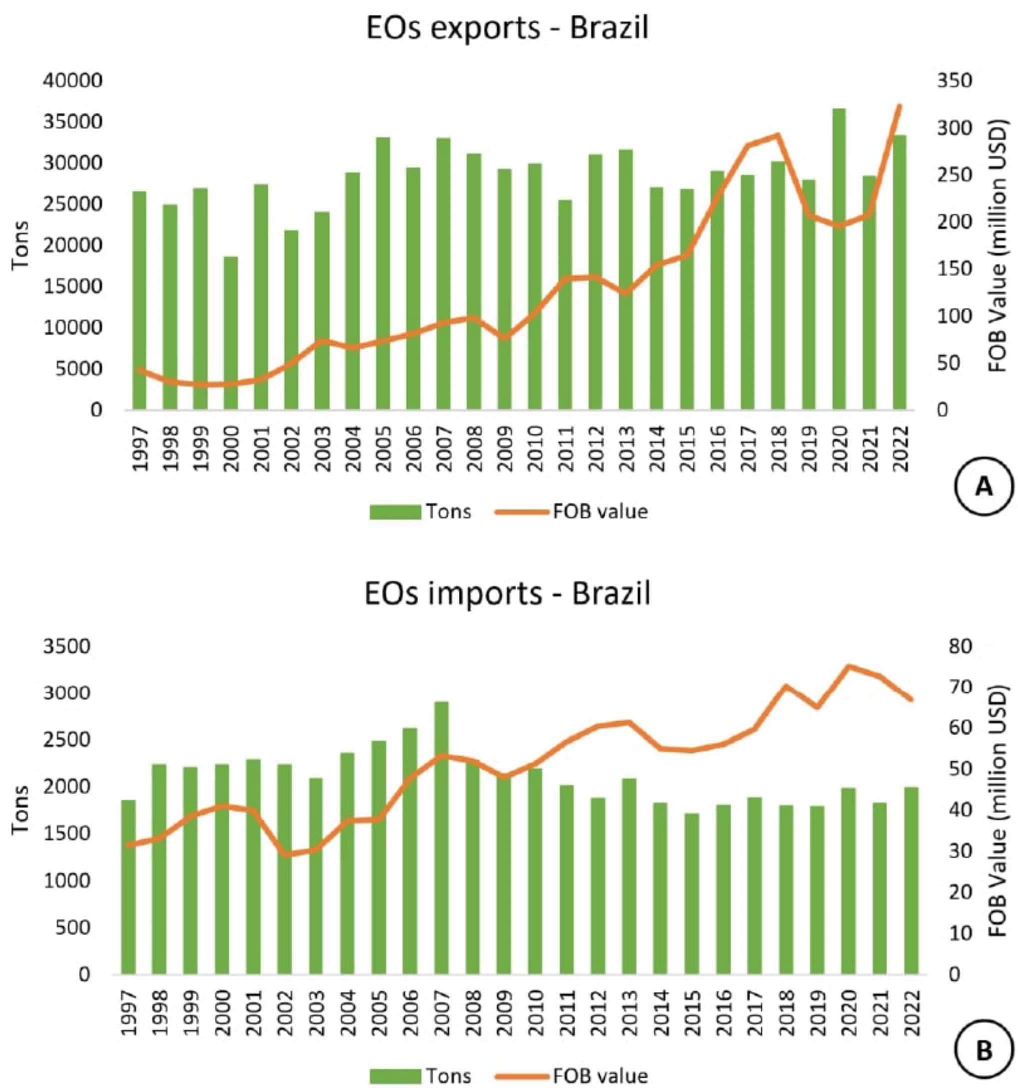

Figure 2. Quantities and values of exported essential oils (A) and imported essential oils (B) in Brazil. FOB: "Free On Board," total price of the goods at the point of shipment, excluding transportation and insurance costs after that point. Source: Comex Stat

In general terms, the market for EOs is economically relevant, with the potential for production expansion in both quantity and explored species. This requires monitoring market advances and demands, structuring the production chain, and always complying with legal requirements.

Future Perspectives and Final Considerations

The data from the "Vegetal Extraction and Forestry Production – PEVS 2021" of IBGE show that the eucalyptus area for commercial purposes in Brazil is 7.3 million hectares, with 45.4% of these areas located in the southeastern region (IBGE, 2021). The germplasms currently being used, according to the Brazilian Agricultural Research Corporation (EMBRAPA), are: *E. benthamii*, *E. dunni*, *E. grandis*, *E. saligna*, *E. urophylla*, *Corymbia citriodora*, hybrids of *E. grandis* x *E. urophylla*, and other interspecific hybrids; these materials are chosen based on the characteristics of their wood, economic importance, adaptability, and resistance to pests and diseases (Embrapa, 2022).

Eucalyptus globulus is also very interesting for the EOs market, mainly due to its eucalyptol content, but also for being a species adapted to colder regions and cultivated only in southern Brazil. However, analyzing the collected data in the literature, it is noticed that other eucalyptus

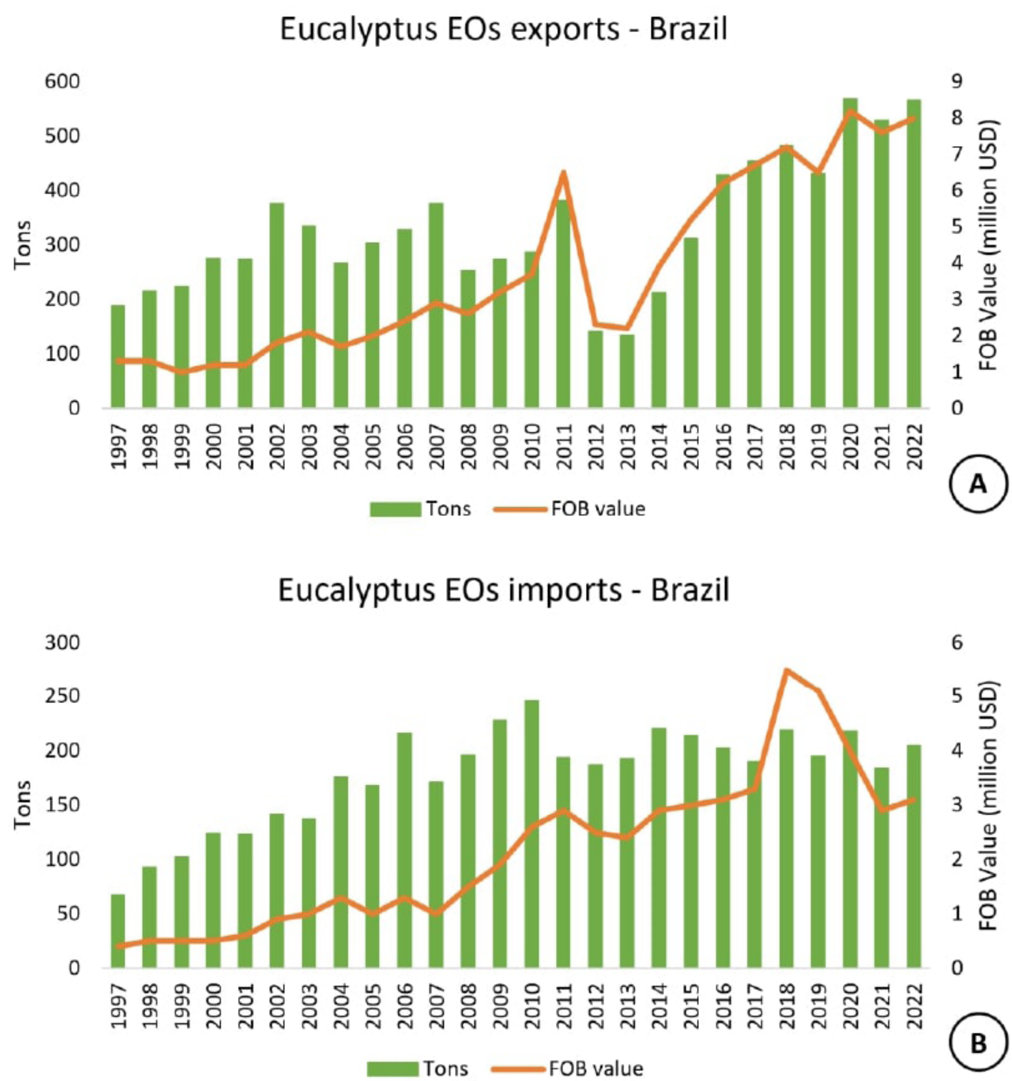

Figure 3. Quantities and values of eucalyptus essential oils (EOs) exported (A) and imported (B) in Brazil. FOB: "Free On Board," total price of the goods at the point of shipment, excluding transportation and insurance costs after that point. Source: Comex Stat

species besides *E. globulus* have presented EOs with eucalyptol percentages exceeding 60%, such as *E. camaldulensis* in Egypt (Salem *et al.*, 2016), *E. dunnii* in Argentina (Santadino *et al.*, 2017), *E. exserta* in Tunisia (Elaissi *et al.*, 2011), *E. saligna* in China (Lu *et al.*, 2014), and *E. urophylla* in Brazil (Filomeno *et al.*, 2016). In two *E. saligna* EO from leaves collected in Brazil (Filomeno *et al.*, 2016) and Argentina (Toloza *et al.*, 2006), percentages of 92% and 93% eucalyptol were recorded, respectively. In other words, in addition to scientifically unexplored species, there is potential to expand the EOs market by adding more value to species already cultivated for timber purposes.

Considering all the variables that interfere with EO chemotypes, more advanced chemical, biological, and data analysis techniques must be applied to study and map the biotic and abiotic conditions that define specific oil compositions and the mechanisms and modes of action involved. Due to the already discussed complexity of these products, many researchers evaluate the effect and mode of action of isolated actives (usually the most representative in EOs); these studies should be encouraged and continued, but evaluations of combined actives are also necessary to test possible additive, synergistic, or antagonistic effects that may still be unknown.

It is essential to emphasize that in addition to the comprehensive number of factors to be controlled, there are also numerous eucalypt species and possibilities for the application of EOs and their actives. The lack of study of some species because they are already considered for a particular purpose may prevent the discovery of effective products for other purposes. All these points generate an infinity of possibilities for studies, which should always document all plant characteristics, location, collection, extraction, and oil analysis whenever possible.

Although many studies present benefits and the responsible and safe use of EOs, possible negative or undesired impacts can also be obtained; this type of response is found less frequently in the literature but should be equally documented when obtained.

With more consolidated data related to raw materials and efficacy, another challenge is to make viable the use of these products through formulations that provide EO stability and are suitable for each application and objective, since one of their main characteristics is high volatility.

Economic aspects should also be addressed to stimulate the entire previously mentioned process. The production and marketing of EOs have the potential for expansion and must be organized to ensure the quality and reliability of the products, as it is a market that supplies other countries with specific requirements and diverse uses. Even for internal use, oils need to meet certain standards to be used, and considering this economic context, in addition to specific constituents, another factor to be considered is the oil yield of the selected eucalyptus species.

A quick way to assess interest in EOs is by surveying published works on the topic. Searching for the terms "essential oil" and "*Eucalyptus*" as topics in the Web of Science yielded 1945 works (publications between 1900 and 2023). When limiting this search to the last ten years, 1265 publications are found, showing that it is a topic that has been more studied in recent years.

Solutions to problems faced today may be present in elements available in nature, such as EOs, which can be an alternative source for the development of natural medicines and more sustainable bio-inputs. Companies are increasingly interested in these products that can act through different mechanisms against microorganisms already resistant to traditional agents or generate new solutions. Thus, the more information and solutions obtained, the more viable this market will be, including financially.

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Authors' Contributions

Conceptualization: Rodrigues M., Mazzafera P. Writing-original draft: Rodrigues M. Writing review & editing: Rodrigues M, Mazzafera P.

Conflict of Interest

The authors declare no conflicts of interest (personal, scientific, commercial, political, or financial) in the submitted manuscript.

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